An Agent-Based Simulation of Avian Influenza Outbreaks

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1.1.1 Background of the Chosen Case and Motivation

Compared to highly pathogenic strains, low pathogenic avian influenza (LPAI) often causes milder symptoms and lower fatality rates, mostly affecting the respiratory and digestive systems of birds. LPAI typically causes milder symptoms and lower mortality compared to highly pathogenic strains. However, it can occasionally mutate into highly pathogenic avian influenza (HPAI), leading to more severe outbreaks. Moreover, long-distance transmission of the virus is made possible by wild birds, which act as reservoirs for the infection and complicate containment attempts. The difficulty of controlling epidemics is heightened by their long-distance transmission, especially in domestic poultry flocks (Elbers et al., 2004).

1.1.2 Suitability for Agent-Based Modelling

ABM enables specific examination of individual transmission dynamics by allowing each bird agent to have unique characteristics such as age and health condition (susceptible, exposed, infected, recovered, or dead). The ability of ABM to replicate real-world variables that affect transmission and mortality rates, like temperature and cleanliness, is a major advantage. These parameters can be changed by researchers to assess the effects of treatments like immunization, quarantine, or culling. ABM also simulates spatial dynamics, monitoring contacts and movements of birds, assisting in the identification of hotspots for transmission and evaluating the impacts of biosecurity or mobility limitations (Perez & Dragicevic, 2009).

1.1.3 Complexity and value of the Case for Simulation

Bird density and interaction frequency have a major influence on the spread of the virus, with crowded environments favoring more contact between susceptible and infected birds. The age and duration of exposure of a bird dictate when it becomes sick or recovers throughout the incubation and infection stages, which are also taken into consideration by the model. Environmental variables like temperature and cleanliness have an impact on mortality and recovery rates. By simulating different circumstances, policymakers and farm managers may benefit from this research's insightful recommendations on how to cut expenditures, enhance public health responses, and lessen the likelihood of outbreaks.

1.2 Model Design

1.2.1 Agent Description:

Bird Agent: Each bird agent represents an individual chicken with health states (Susceptible, Exposed, Infected, Recovered, Dead) based on the SEIRD model (Mathews et al., 2007). We differentiate between young and adult birds due to age-related differences in disease parameters (Keeling & Rohani, 2011).

Attributes: incubation_period, infection_period, base_transmission_rate, base_mortality_rate, immunity_duration

State Transitions: Birds transition between states (S → E → I → R/D, R → S) according to the SEIRD model structure.

Environment: Our model simulates a poultry farm using a 12x12 2D grid. We incorporate dynamic environmental factors (temperature and hygiene level) that affect transmission and mortality rates (Hosseini et al., 2013).

Rules:

- **Movement:** Birds move randomly to adjacent cells in each time step, simulating natural movement within a confined space (Comin et al., 2011).
- **Interaction:** Disease transmission occurs between infected and susceptible birds in the same cell, influenced by environmental factors (Hosseini et al., 2013).
- **State Update:** Bird health states are updated each time step, with mortality rates affected by environmental factors.

Initial Configuration: 80 birds (8 exposed, 72 susceptible) on a 12x12 grid, with equal young and adult distribution, based on real-world scenarios (Gao et al., 2013).

Complexity Reflection

- **Transmission Complexity**: Incorporates environmental factors and age differences.
- **State Transitions:** Includes latent period, variable recovery time, and temporary immunity (Mathews et al., 2007).
- **Spatial Movement:** Random movement with initial concentrated distribution (Comin et al., 2011).
- **Environmental Dynamics:** Feedback loop between disease spread and environmental conditions (Hosseini et al., 2013).

1.2.2 References

We have integrated important components from current epidemiological data into our agent-based model of avian influenza transmission. It uses a 2D grid to depict spatial dynamics and combines an age-structured chicken quantity (Keeling & Rohani, 2011) with an SEIRD structure (Mathews et al., 2007). According to Hosseini et al. (2013), environmental factors impact both transmission and fatality rates. Gao et al. (2013) based initial parameters on real-world outbreak data. By capturing the intricate interactions between many factors influencing disease dynamics in poultry populations, this model seeks to offer a platform for investigating potential intervention approaches and epidemic scenarios.

1.3 Simulation Results and Analysis

Based on Figure 1 to Figure 6 on the appendix, we conducted the following analysis:

1.3.1 Visualization Analysis

The state and behavior of every individual chicken in an ABM (Agent-Based Model) simulation dynamically vary in response to external stimuli like temperature and hygienic conditions. The simulation's displayed charts allow one to see how the virus spreads in various environmental conditions.

Fixed Temperature at 20°C:

- **Hygiene level 0.8**: In high hygiene conditions, the infection rate is low, and most chickens remain healthy. The limited spread of infection suggests effective disease control due to reduced interaction leading to fewer transmissions.
- **Hygiene level 0.5**: As hygiene decreases, the spread expands, but moderately. While virus transmission is possible, the spread remains slower, linked to individual behavior and environmental hygiene in the ABM model.
- **Hygiene level 0.2**: Poor hygiene accelerates the spread significantly, rapidly reducing the number of healthy individuals. This shows how increased interaction and environmental degradation lead to faster virus transmission.

Fixed Hygiene Level at 0.6:

- **Temperature 25°C**: At moderate temperatures, the epidemic spreads slowly, with infections and recoveries rising gradually. The ABM model reflects the dynamic interplay between individual interactions and immune recovery.
- **Temperature 30°C**: Higher temperatures accelerate transmission, with rapid increases in both infection and recovery. The ABM model highlights enhanced virus transmission and faster interaction rates among individuals.
- **Temperature 35°C**: At high temperatures, the epidemic intensifies, with infections surging and recoveries lagging behind. The ABM model shows how temperature boosts virus transmission while recovery takes more time.

1.3.2 Quantitative Analysis

From the quantitative charts of the model, key data on epidemic spread can be extracted, allowing further analysis of how different hygiene conditions and temperatures affect the spread of avian influenza.

Hygiene Impact:

- **Hygiene level 0.8**: In high hygiene conditions, infection remains minimal, with healthy individuals consistently above 50 and infections limited to single digits. This indicates that high hygiene effectively suppresses the spread, as the ABM model shows lower interaction frequency and reduced infection risk.
- **Hygiene level 0.5**: At moderate hygiene, infections increase gradually, reaching 15-20 after timestep 20, while recoveries also rise. This demonstrates controlled spread even as the infection accelerates under moderate hygiene conditions.
- **Hygiene level 0.2**: Poor hygiene leads to a rapid spread, with infections exceeding 30 after timestep 20. This reflects how increased contact and environmental degradation speed up the outbreak, as the ABM clearly captures this acceleration.

Temperature Impact:

- **Temperature 25°C**: At 0.6 hygiene, infection spreads slowly, with healthy individuals above 40 and infections around 10. This suggests moderate temperatures suppress epidemic spread.
- **Temperature 30°C**: The spread accelerates at 30°C, with infections and recoveries both rising sharply after timestep 20. The ABM highlights individual sensitivity to temperature.
- **Temperature 35°C**: High temperatures lead to peak spread, with healthy individuals decreasing sharply and infections exceeding 30 after timestep 30. This shows how high temperatures intensify the outbreak through increased transmission.

This quantitative research reveals that temperature and cleanliness standards are important factors in the epidemic's propagation. Improved cleanliness practices effectively reduce the spread, while higher temperatures hasten it. The intricate relationships between a person's behavior and the spread of viruses are captured by the ABM model. The current simulation results do not show these age-related effects, even though our model design accounts for differences in transmission rates and latency between young and adult birds. This could be because the effects of environmental factors, like temperature and hygiene, are more significant in the short term, masking the effect of age differences.

1.3.3 Parameter Impact

Through the ABM simulation, the effects of external parameters on the spread of avian influenza are evident:

Temperature Impact: Higher temperatures accelerate the spread. At 30°C and 35°C, infection rates rise sharply, and healthy individuals decrease rapidly. This suggests that the virus is more active in higher temperatures, leading to increased transmission. The ABM model shows how temperature directly influences behavior and infection rates.

Hygiene Impact: Poor hygiene worsens the spread. At low hygiene levels (0.2), infections rise quickly due to increased contact and environmental contamination. Conversely, better hygiene significantly slows transmission, keeping infection numbers low. The ABM model demonstrates how hygiene directly affects individual infection risks.

Understanding these parameters highlights the importance of temperature control and hygiene management to prevent widespread outbreaks. Ignoring them could result in uncontrolled epidemic spread.

Mechanism Analysis: Hygiene conditions impact virus transmission by affecting its environmental survival and spread. Poor hygiene leads to accumulation of organic matter, providing more opportunities for virus persistence (Bertran et al., 2017), explaining sharp infection rate increases in low-hygiene settings.

Temperature influence is multifaceted. Higher temperatures accelerate virus replication and potentially increase bird stress, lowering immunity (Mooring et al., 2020). Additionally, heat alters bird behavior, such as increased drinking frequency, enhancing contact with contaminated sources (Poulson et al., 2022). These factors collectively contribute to faster epidemic spread in high-temperature environments.

1.3.4 Real-World Reflection

Based on the ABM simulation, the following real-world implications for avian influenza control emerge:

- Climate Adaptation: Model shows that temperature has a significant effect on disease transmission. At higher temperatures (such as above 30°C), the propagation speed is significantly accelerated. Therefore, temperature control measures are recommended for poultry farms, especially during the warm season (Seyed Ghafouri et al., 2023).
- Rapid Detection: Implement advanced technologies such as CRISPR/Cas12a for quick and accurate virus detection (Yin et al., 2022).
- Vaccination Strategies: Develop and utilize effective vaccines that comply with regulatory requirements (Swayne & Spackman, 2020).

1.4.1 Summary

Key discoveries on the transmission of LPAI are emphasized by the simulation. Increased avian contacts and inadequate cleanliness both contribute to the rapid spread of viruses in high-density places such as poultry farms, underscoring the need of biosecurity. Since asymptomatic birds in the incubation period continue to spread the virus, early intervention is essential. Increased vaccination rates and improved cleanliness drastically lower illness and death rates. While moderate temperatures and improved sanitation reduce infection rates, higher temperatures (over 28°C) increase bird mortality (Hénaux, Samuel, & Bunck, 2010).

1.4.2 Limitations

The model overlooks individual health and behavioral variances and oversimplifies real-world elements by assuming a consistent transmission rate for all birds. Additionally, the movements of birds are modeled randomly, ignoring more intricate patterns such as territoriality or group dynamics.

1.4.3 Future work

More precise environmental elements, such as seasonal fluctuations or climatic shifts, and improved bird interaction models that capture realistic movement and behavior patterns are potential future enhancements. Furthermore, adding health aspects to the simulation, such as immunological weaknesses, might improve its accuracy.

References

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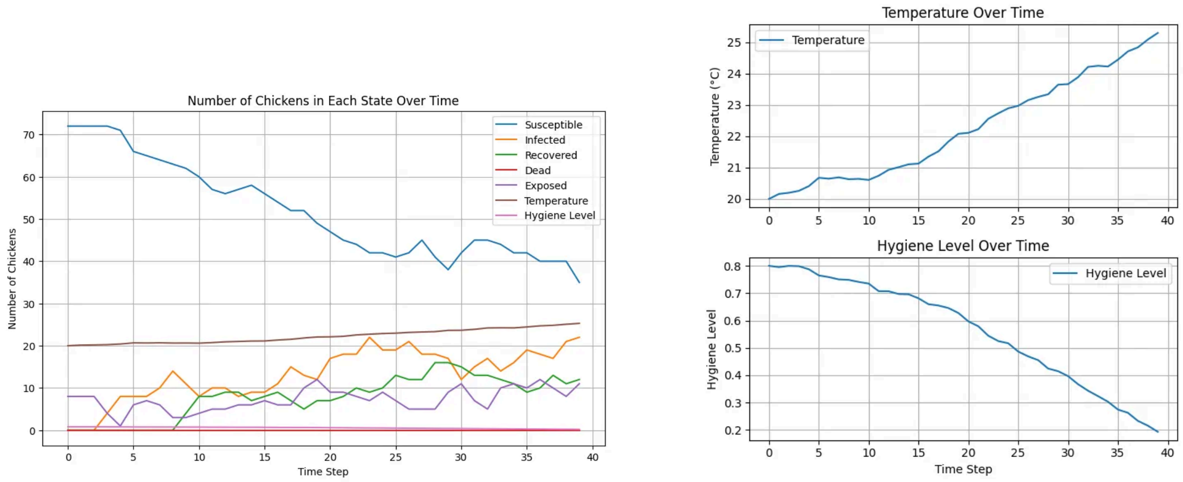
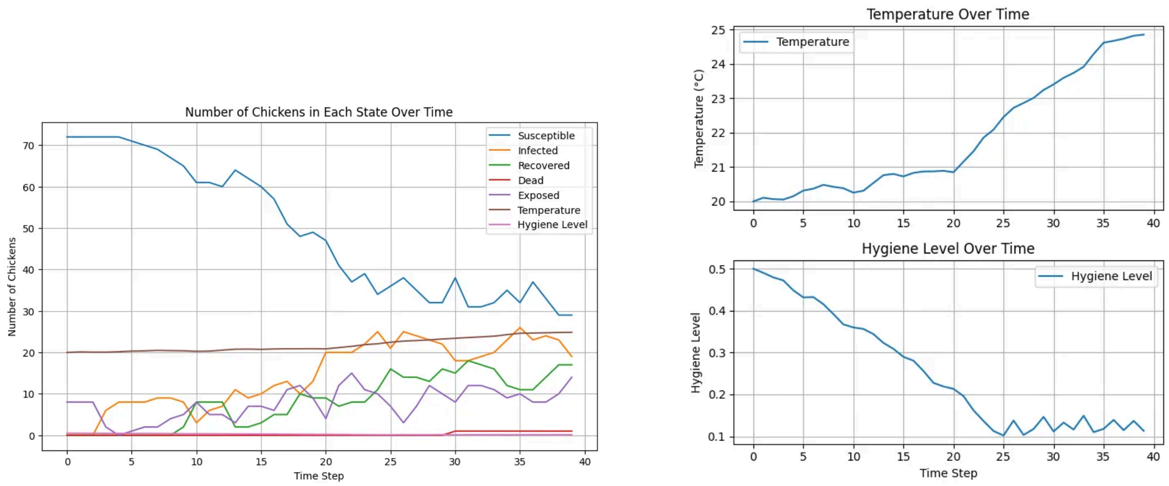
Appendix

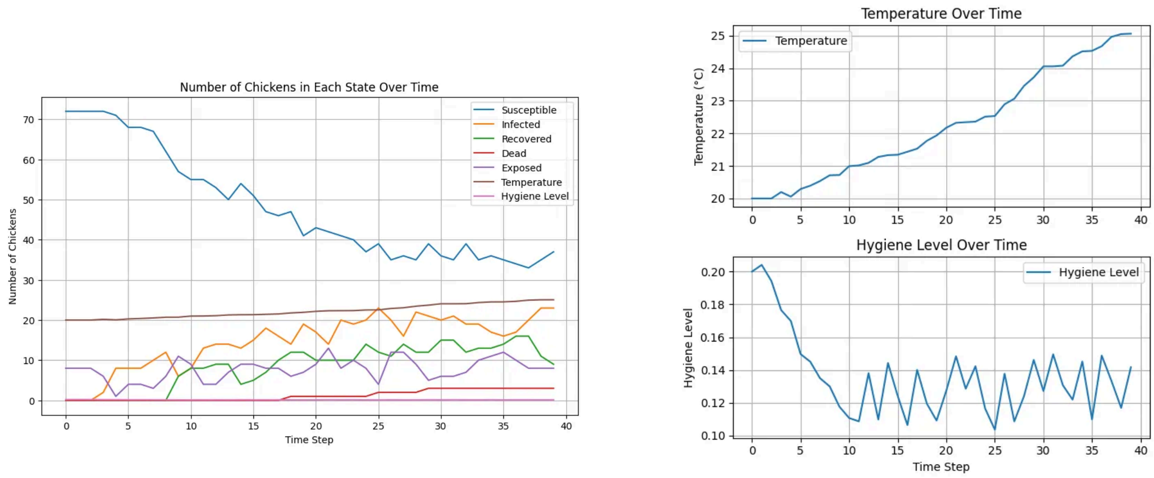
Temperature: 20 Sanitary condition: 0.8 (Figure 1)



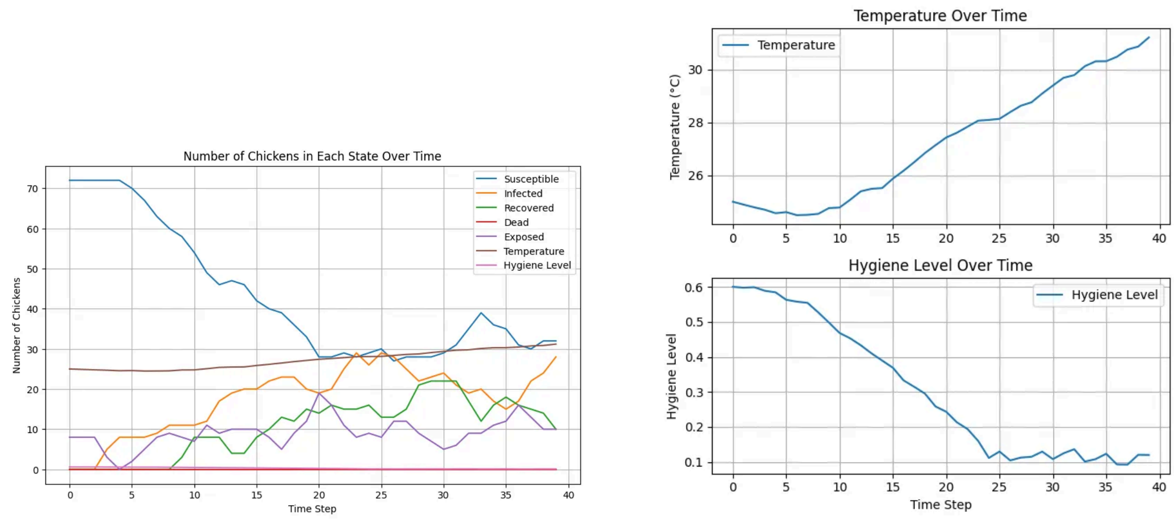
Temperature: 20 Sanitary condition: 0.5 (Figure2)



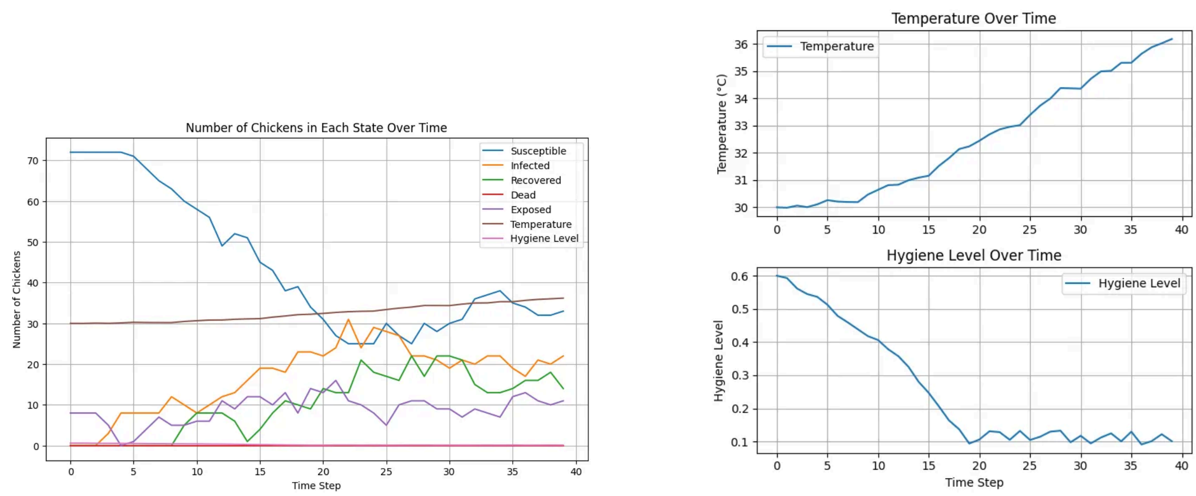
Temperature: 20 Sanitary condition: 0.2 (Figure 3)



Temperature: 25 Sanitary condition: 0.6 (Figure4)



Temperature: 30 Sanitary condition: 0.6 (Figure5)



Temperature: 35 Sanitary condition: 0.6 (Figure6)